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THEORETICAL AND EXPERIMENTAL STUDY

OF IGNITION LAG AND ENGINE KNOCK

By Fritz A. F. Schmidt

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SUMMARY

The author believes, on the basis of experimental
ignition-lag data, that the character of a fuel cannot
be stated in terms of a single constant (such as octane
or cetene number) but that at least two and generally
three constants are required.

Thus no correlation between knock ratings can be
expected if in one set of tests the charge temperature
was varied while in the other the charge pressure was
varied.

For this reason, he favors knock rating being based
on an equation characterizing the ignition lag of the
fuel as a function of pressure and temperature of the
charge.

I. INTRODUCTION


The individual processes accompanying the combustion
in an engine are so complicated as to make their investi-
gation extremely difficult. However, experiments with
engines have made it possible to calculate the total proc-
ess of combustion and particularly the end of combustion,
by determination of the burnt fuel volume in relation to
the crank angle. In the attack on this problem, the
studies with calorimetric bombs (references 1 to 5) and in
pipes (references 6-11, 29, 30) have proved very valuable.
For instance, the ignition lag values were also measured

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in this manner. But the manner in which in these tests the chemical change of the fuel molecules with the oxygen takes place, has not been sufficiently explored. The exact calculation of the reaction process has up to the present been successful for very few reactions following a known pattern (for instance, bimolecular reactions, etc.) (reference 12), while the data on the reaction at oxidation of complex compounds are very incomplete (references 6 and 9). Even more difficult is the investigation of commercial fuels incorporated of a large number of complicated blends.

But, for commerical purposes, it is not necessary, in the majority of cases, to know all partial processes; it suffices to determine the regularity of the total process as total result. Engine studies would be much easier if the phenomena observed during combustion could be traced back to a minimum of fundamental laws. The good reproducibility of ignition-lag tests and the fact that the combustion processes reproducible within certain limits can be influenced by physical conditions (for instance, pressure, temperature) seem to indicate that it might be possible to ascertain the processes accompanying combustion accurately enough for engineering purposes by standard methods based on few laws even without knowing the exact mechanism of reaction. Once the fundamental laws are accurately enough available, it should be possible to draw some important conclusions for the improvement in fuel testing and development. For the interpretation of engine tests, it is of particular importance to establish the relationship existing between the physical test of combustion in a pipe, the combustion in the calorimetric bomb (for example, ignition-lag measurements) and the processes accompanying the combustion in Otto and Diesel engines in order to be able to deduce from these physical tests simple relations which can be applied to the complicated engine tests. Then it would be possible to follow the combustion process mathematically under any change in physical assumptions, such as at the different pressure and temperature changes due to piston stroke or the movement of the flame front.

In the following the relations between engine and bomb test data are discussed on the basis of theoretical considerations.

II. IGNITION LAG

1. Generalities

Numerous ignition-lag measurements in engines and calorimetric bombs have proved a definite connection between ignition lag period,* temperature, and pressure (references 13, 2, and 5). Since it was possible to extend the bomb studies over a wide temperature and pressure range the findings are very accurate. But the allocation of ignition lag in the engine to certain temperatures and pressures is uncertain because of the rapid changes in these two quantities. Aside from that, the scope of investigation is very limited on account of the short time available and the thus imposed narrow limit for maximum ignition lag.

The elucidation of the causes of ignition lag in the engine and in the bomb calls for an investigation of the thermal processes involved, i.e., of the processes of heating and vaporization, as well as of the chemical changes, that is, of the reactions.

Theoretical and experimental studies have shown that the thermal processes, especially the heating and vaporization cannot be the sole causes of ignition lag. In support of this, we computed the mean temperature rise and the time rate of vaporization of fuel droplets with due allowance for the variable drop velocity, using Wetzel's calculation (reference 14) as basis.

Various simplifying assumptions were necessary among others, constancy of air temperature at spray boundary, equal drop size at spray boundary and in spray core, and a distribution of fuel droplets and of the air in the spray core in correspondence with estimated mean values from engine tests (average $\lambda = 0.4$, air temperature 550° C., pressure 34 atm.). The quantity of air in the spray zone was averaged, because of the continuous expansion of the spray and hence of the mixture ratio during the ignition-lag period. The study discloses, for the spray core, that the time lapse for equal temperature adjustment, can exceed that at the spray boundary considerably (from 20 to 50 percent for the temperature range chosen in the example).

Although the simplifying assumptions are not alto-

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*The absolute ignition-lag figures for different fuels are markedly at variance.

gether true to fact as the drop size at the edge is smaller
than in the core, the sought-for results are nevertheless
correct in order of magnitude, and so afford a possible
comparison of the conditions in the spray core  and at the
spray boundary.  For average drop distribution according
to Sass (reference 15)* about 80 percent of the fuel volume
is already vaporized at the spray boundary 5/10 000 second
after start of spray (fig. 1).

But the ignition-lag periods of several thousandths
of a second and even above 1/100 second (at low tempera-
tures), particularly in bomb experiments, cannot be ex-
plained by the vaporization process alone; even during the
short ignition-lag period in the engine the greater part
of the fuel is vaporized in many cases in the spray start
interval, so that no systematic relation can be ascertained
between vaporization period and total ignition-lag period.
It is therefore proper to divide the total ignition lag
into a process due to thermal (heating and vaporization)
and a process due to chemical causes (chemical reactions
during ignition-lag period).  Since both processes overlap
to a certain extent, the determination of the total igni-
tion-lag period by addition of the two calculated separate-
ly, is not rigorously correct, but nevertheless permissi-
ble for first approach.

It may be considered proved that the ignition starts
at the spray boundary and at several places (simultaneously
in part), hence the ignition does not, according to the
Diesel principle start from a single core.  The combustion
starts simultaneously at many points.

Figure 2 is an enlarged view of fuel spray at 1 at-
mosphere.  The light source was an electric spark afford-
ing a period of exposure of $10^{-6}$ seconds with a luminous
intensity of the spark of around  $6 \times 10^5$ HK.  In the low-
speed range the photographs of the fuel drops are circles,
at higher speed the circles turn into bands if the travel
of the drop, during exposure, is considerable in relation
to its diameter.  High velocity exists in the spray core,
especially in proximity of the nozzle-exit orifice, whence
the fuel drops form long streaks.  At the spray border the
velocity of the drop slows up consistently, hence the drops
appear almost as circles.  At the spray tip a large volume
of fuel accumulates as a result of the retarding effect of

*Jung's more recent tests (optic observation of droplets
in spray) in the DVL give similar results.

the air. From the process, figures 2 and 3, it may be
inferred that the drops with low speed at the spray bound-
ary are enveloped by fairly large air masses and are heat-
ed quickly, hence ignite first. This is also in accord
with the optical observations and the findings from studies
by the ionization method into the start of ignition. The
comparatively larger fuel masses moved forward in the spray
tip do not heat as readily because of the comparatively
small air volume available for heating. Stroboscopic rec-
ords also reveal the spray tip as being continuously fed
from within, whereas drop masses at the sides remain be-
hind, so that the spray tip must always be colder than the
spray envelope. The drops farther away from the spray be-
come heated and vaporized and readied for igniting.

The calorimetric bomb ignition lag tests were mostly
extended into the range of very low temperatures (up to
about 350° C.). In this zone a very pronounced tempera-
ture relation was ascertained, which earlier experimenters
expressed empirically with a function $e^{b/T}$. This rela-
tionship is, as demonstrated by the subsequent considera-
tions, evidently largely attributable to chemical causes.


## 2. Theoretical Studies

For the purpose of explanation of the fundamental
influences so far as they relate to the chemical propor-
tion of the ignition lag, the ignition-lag period will be
computed for the simple case of reaction between two
gases, the assumption being a slow reaction at start but
subsequently accelerated as a result of the temperature
rise. The period of ignition lag is defined as the in-
terval up to reaching the temperature $T_z$. (The exact
determination of $T_z$ is usually of secondary influence on
the result of the calculation, as the temperature rise at
the end of the ignition lag is extremely rapid.) These
premises were chosen in order to obtain an agreement with
the findings from ignition-lag experiments. The first
flash of light is generally accepted as characteristic
sign for the start of ignition.* The chosen definition

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*This assumption is arbitrary, since a combustion is under
way even before the appearance of the visible light. Sim-
ilarly in flame photographs the so-called "flame front" is
not the border of the combustion start, since combustion
prevails in front of it in the part of the unburnt mixture
not illuminated as well as behind in the illuminated part,
as a result of which the flame front actually has some
thickness. A. M. Rothrock and R. C. Spencer (reference 30)
have shown that there is a certain late burning even behind
the flame front.

can, moreover, be readily reconciled with other test meth-
ods, since the ignition lag whether obtained by ionization
method, by optical method, or as determined from the pres-
sure rise, is of the same order of magnitude (reference
16). The definition of ignition lag by reaching a combus-
tion velocity which is determined for a preponderance of
heat released by combustion relative to that dissipated by
the exhaust, favors the results only in the proximity of
the ignition limits. If the temperatures are far above
these limits, as, for instance, for ignition in the engine,
the heat removal is of secondary importance.

Based upon the above definition, the ignition lag can
be theoretically computed for simple cases (reference 32).
The calculation is fairly simple for standard gases with
known reaction mechanism. For illustration, the deriva-
tion for a bimolecular reaction at which no chain reac-
tions take place is given:

Compute the time interval following from the inte-
gration of the time elements  dz  for the combus-
tion process in the whole temperature range from
start of reaction to temperature  $T_z$.

Allowing for the impact figure of the molecules and
assuming that a reaction between two molecules can take
place only when its total amount exceeds a certain value
$Q_a$,* the fuel volume  $d[B]/dz$  converted in unit time
follows, at:

$$\frac{d[B]}{dz} = \pi(r_1 + r_2)^2 \sqrt{\overline{w}_1^2 + \overline{w}_2^2} \; N_L [O_2][B] e^{-Q_a/RT} \qquad (1)$$

where  $e^{-Q_a/RT}$  is the proportion of the successful shocks.

In this formula

$r_1$, $r_2$     indicate the mean radii of the reacting
                molecules

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*The processes accompanying the activation are not defi-
nitely known; not every shock of activated molecules must
of necessity lead to reaction. However, the details and
limitations are without the scope of this report.

$\overline{w}_1$, $\overline{w}_2$,   the roots from the mean velocity square of the oxygen and fuel molecules

$N_L$,   the Loschmidt number

$[O_2]$,   the molecular concentration of oxygen

$[B]$,   the molecular concentration of fuel

$R$,   the gas constant

$T$,   absolute temperature

According to Maxwell's law of velocity distribution the proportion of the molecules whose energy exceeds a certain amount $E$ corresponds to an exponential function $e^{-E/RT}$. The frequency of reaction on collision of two molecules is contingent on the probability that the sum of the energies of the two molecules exceeds a certain minimum value $Q_a$. And this relation holds not only for the kinetic energy of translation but for other forms of energy as well (such as oscillation, rotation, for instance), hence can be introduced generally. The above relation is further supported by test data, since the value $e^{-Q_a/RT}$ can also be obtained empirically.

The heat of activation $Q_a$ could be successfully defined in several reactions from the absolute quantity converted in unit time at a certain temperature, as well as from the change of conversion velocity with temperature (empirical formula by Arrhenius). Hereby, the value $Q_a$ was found to be little affected by temperature, whence it is permissible to consider this value constant in a limited temperature range. The exponential function indicates an extremely great rise in reaction velocity with temperature, so that for the whole duration of a reaction the part at start and at lower temperature, respectively, is largely decisive. The lower the value of $Q_a$, the smaller is the effect of temperature on the rate of temperature rise.

From the equation of the reaction velocity (equation (1)), the duration for the ignition lag can be obtained by integration in the range between initial temperature and temperature $T_z$. It gives:

$$Z = \int_{T_1}^{T_z} \frac{e^{Q_a/RT}\, d[B]}{\pi(r_1 + r_2)^2 \sqrt{\overline{w}_1{}^2 + \overline{w}_2{}^2}\, N_L [O_2][B]}$$

the differential of the converted fuel volume is substi-
tuted by a function of  T.  It gives:

$$d[B] = \frac{\Sigma[]\, M\, c_p\, dT}{H_u} \tag{2}$$

where the summation extends over all interested gases
corresponding to their molality at the particular temper-
ature ($H_u$ = heat value of fuel,  [] M $c_p$ = molality × molal
heat).

Introducing the initial concentration and replacing
it with the aid of the combustion equation by a function
of the specific heats, the heat value and the maximum tem-
perature rise at complete combustion of the total fuel
($T_{max} - T_1$):

$$[B]_1 = \frac{(T_{max} - T_1)\, \Sigma[]^{T_{max}}\, m\, c_{p\,m}\, \Big|_{T_1}^{T_{max}}}{H_u}$$

we find, after several changes:

$$z = \frac{T_1}{p_1}\left(\frac{1}{T_{max}-T_1}\right)c \int_{T_1}^{T_z} \frac{e^{Q_a/RT}}{\sqrt{T}}\cdot\frac{[O_2][B]_1}{[O_2][B]}\cdot\frac{\Sigma[]^T}{\Sigma[]^{T_{max}}}\, dT \tag{3}$$

where:

$$c = \frac{p_0\, M\, c_{p_1}}{T_0 M c_{p\,m}\Big|_{T_1}^{T_{max}} \sqrt{3 R g \left(\frac{1}{M_1}+\frac{1}{M_2}\right)}\, \pi(r_1 + r_2)^2\, N_L [O_2]_0} \tag{4}$$

($p$ is pressure, $T_{max}$,  maximum temperature of combustion
at constant pressure, computed for the heat value of the

total fuel; $M_1$, $M_2$, molecular weights; g, acceleration of gravity; index 0, the normal state (for instance, $15^\circ$ C. and 1 atm. abs.), index 1, the initial state of the reaction).

The variation of the specific heats within the temperature range of the integration being small, the specific heats $c_p$ are expressed as constant. The effect of the counter reaction is not perceptible, since the range for which the ignition lag is computed is remote from the equilibrium condition.

The molal concentrations in equation (3) are dependent on the time and temperature, respectively. But their variations during ignition lag is usually little, so that for practical purposes the concentration is considered constant and equated to the initial concentration. In cases where this is not permissible, progressive integration must be resorted to.

For practical application a presentation of the ignition-lag period in function of the initial state is informative. It gives:

$$z = \frac{e^{-Q_a/RT_1} \sqrt{T_1}}{p_1} a \beta \tag{5}$$

The integration constant can be disregarded since the limit value of the ignition lag is very small for high temperatures. The value $\beta = c/g$ (fig. 4) allows for the reduced lag period resulting from the increased rate of burning during the ignition lag period which is due to the temperature rise within this interval. It can be determined from the relation

$$\beta = \frac{e^{-Q_a/RT_1} \sqrt{T_1}}{(T_z - T_1)} \int_{T_1}^{T_z} \frac{e^{Q_a/RT}}{\sqrt{T}} \, dT \tag{6}$$

where through substitution and partial integration the integral may be reduced to the integral

$$\int_0^x \frac{e^{-x}}{x} \, dx$$ available in tables. The change in $\beta$ with

the temperature is illustrated in figure 5. Value a is
numerically computable; it is little affected by the ex-
cess air figure $\lambda$ (approximately corresponding to $T_{max}$ -
$T_1$, since $T_{max} - T_1$ is dependent on $\lambda$). An increas-
ing $\lambda$ results in a decrease of a.*

For states of equal, great ignition lag, it is:**

$$\ln p_1 = \frac{Q_a}{R\ T_1} + \frac{1}{2} \ln T_1 + \ln \beta + const$$

While the heat removal during the ignition processes in an
engine plays a comparatively small part, it is of decisive
importance for the determination of the autoignition tem-
perature and must therefore be accounted for since the
lowest limit of autoignition is conditioned by the excess
of developed, relative to evacuated, heat.

### 3. Physical and Chemical Processes during Autoignition

The foregoing deductions are for the present appli-
cable only to the simplified assumptions, to which the
mechanism of reaction of only a few reactions corresponds.
In point of fact the majority of reactions pass through
intermediate stages, so that various reactions become
superposed, which in many cases are preceded by cleavage
processes. Then, too, it must be assumed that the combus-
tion process in nearly all technical cases is by way of
chain reaction.

Since at combustion in a Diesel engine and in similar
bomb tests with liquid fuel injection, the ignition takes
place in small zones of the spray boundary which are no
longer affected by the wall, there is no wall effect.
Hence arguments and deductions based on chain interruption
at the wall are ruled out. The reaction mechanism of com-
mercial fuels is surprisingly little known; even for ele-
mentary substances such as methane the course of combustion

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*For impirical presentation of test curves on ignition-lag
values, a, $\beta$, $\sqrt{T}$, may be considered constant. In this case
a somewhat higher mean temperature takes the place of $T_1$.

**Other investigations into the relationship existing be-
tween the minimum pressure and temperature at which autoig-
nition occurs known from literature have resulted in a sim-
ilar formula but with different constants.

is so complicated that no definite explanation has ever
been published. It is known, for instance, that the
methane combustion is over methanol and formaldehyde.
CC. and CH bands were also observed. The intermediate
products continue, in part, to disintegrate under heat.
The products obtained on the basis of such observations
correspond to several intermediate reaction stages, so that
for the final termination of the reaction process several
shocks are required. Even for the chain reactions the
conversion processes are still not accurately known, hence
a purely theoretical derivation of the ignition lag is for
the present impossible for these substances.

From the reproducibility and uniformity of the regu-
larities of the test data for changing pressure and tem-
perature it can be concluded that the frequency of reac-
tion start is so great that the disparity of the individ-
ual processes during the course of reaction does no longer
appear in the measurement of the total process.

The assumption also suggests itself that the chain
reactions produced by the first reaction of fuel molecules
are numerous enough to justify their expression by a mean
reaction. Besides, the observations of the processes ac-
companying ignition at the fuel spray lead to the concept
that the reaction starts at a particularly propitious
point, favored on the one hand by conditions conducive to
heating of the droplets, i.e., high temperatures, and on
the other, by the presence of optimum mixture ratio. Since
ample reaction or molecular shock* frequencies are possible
even in a very small space compared to the fuel spray, it
may be assumed that in every fuel spray the optimum mixture
ratio exists at several points. The reproducibility of the
experiments vouches for the fact that in tests under iden-
tical initial conditions the assumptions for the creation

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*The order of magnitude of the shock frequencies is appar-
ent, for instance, from the fact that at a pressure of 30
atm. and a temperature of $500^\circ$ C. the shock figure of a
molecule already amounts to about $10^{11}$ per sec., with the
order of magnitude of the radius of the molecule at $10^{-8}$ cm.
In 1 $mm^3$ the number of molecules would amount to $\approx 10^{17}$.
Considering a bimolecular reaction with an activation heat
of $Q_a = 8,000$ R, it gives at $500^\circ$ C. - corresponding to
the factor $e^{-8000/T}$ a successful shock each 30,000 impacts.
The change in the number of reactive molecules with the
temperature is considerable by reason of the dependence on
function e. For the same example every 3,600 shock would
be successful at $700^\circ$ C.

of the optimum mixture ratio are essentially the same -
even though temporarily at different points.

Despite the fact that an exact calculation of the
combustion processes is impossible, the above considera-
tions make it appear feasible that the chemical share on
ignition lag for chain reaction and for nonstandardized
fuels (gasoline, for instance) can be reproduced by a for-
mula similar to the one developed here. Because of the
existing intermediate reaction the pressure appears as
power with an exponent n. Although the reaction mechan-
ism for the processes leading to autoignition during the
ignition-lag period are not known individually, it is
possible to establish, on the basis of the deduction from
the formula for the chemical share of the ignition lag, a
reaction formula with the aid of the measured regularities
which would afford the same result for the relations of
the chemical ignition-lag share as the measurement.

From the formula*

$$z = \frac{e^{b/T} \sqrt{T}}{p^n} \, a \, \beta \tag{5a}$$

for the chemical ignition-lag quota, we obtain in corre-
spondence with the foregoing derivation for the reaction
equation, the expression

$$\frac{d[B]}{dz} = \frac{p^n \, d}{e^{b/T} \sqrt{T}} \tag{8}$$

where d indicates another constant obtainable approxi-
mately from the measured ignition-lag values by approxi-
mate consideration of the thermic ignition-lag share.

Equation (5a) takes account of a temperature rise
during the reaction. In chain reactions the possibility
exists - in principle - that the reaction is very rapidly
accelerated without appreciable temperature rise. (See

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* Value   b   substitutes for value   $Q_a/R$,   since the
physical intepretation of the heat of the activation does
no longer apply here.

Semenoff theories.) The purely isothermic reaction of
fuels, which, on the whole, burn with considerable heat
development, can, however, be only considered as a special
case. The assumption that heat is released even during
chain reaction as a result of the formation of the end
products, is the more general.

The three constants b, n, and d, in equation (8)
should be obtained from the ignition-lag tests by means of
equation (5a). They present in this case no physically ac-
curately defined quantities, but averages to be interpret-
ed as empirical quantities. Obviously the correct defini-
tion of the constants in this equation requires the selec-
tion of the accurate equation of the chemical ignition-lag
quota as a basis, wherein the value $\beta$ is accounted for
conformably to equation (6), or else a wrong value b is
obtained. When computing $\beta$, the value b substitutes
for $\dfrac{Q_a}{R}$ in equation (6). An equation expressing the proc-
ess during time interval dz can be formulated from the
recorded ignition-lag values only with allowance for the
temperature variation during ignition lag, represented
here by the value $\beta$. The change of $\beta$ with the tempera-
ture (fig. 5) is hereby not as important as the allowance
for the absolute value of $\beta$, which is followed by a sub-
stantial reduction of the exponent in the value
$e^{b/T}$, when b is empirically obtained from experiments.
The thus obtained relation is then applicable to other
ignition processes with any other pressure and temperature
change. The constants, of course, must be interpreted
empirically, but the derivation affords a basis of their
significance.

The empirically defined reaction velocity (equation
(8)) computed in this manner from the ignition lag is a
little too low because in the derivation of formula (5)
for the chemical ignition-lag share it was assumed that
the fuel vapor - air mixture manifests the temperature of
air at the point where the reaction sets in. In reality
a certain cooling of the air has taken place at the points
where the fuel concentration reaches higher values as a re-
sult of the heating and vaporization. Hence the computed
reaction velocities according to equation (8) are actually
reached at slightly lower temperatures than assumed in the
calculation.

Since it concerns an empirical formula that charac-

terizes the whole process, the manner in which the reac-
tion actually proceeds (intermediate, chain reaction) is
immaterial. This assumption is borne out by the fact
that even cases with proved intermediate reaction (for
instance, in $CH_4$ combustion) manifest relations which can
be reproduced by formula (5a) within the limits of instru-
mental error. In many cases the character of the reaction
itself changes in higher temperature ranges so that quan-
tity  b  also remains constant for limited temperature
range only. It is perfectly conceivable that for very
short ignition-lag periods and large droplets a nonuniform
reaction in the boundary layer of the drops is involved,
which as partial reaction and in certain zones could
equally appear as predominating reaction. The sudden in-
flammation observed in ignition-lag tests is, according
to the foregoing theory, explainable as a rapid tempera-
ture rise at the end of the ignition-lag period. The tem-
perature rise at the end of ignition lag, which follows

with the function $\dfrac{e^{b/T}\sqrt{T}}{p^n\, d}$  (equation (8)), when employing

the conventional calculation of the combustion tempera-
ture, is so steep when based on the constants  b  and  n
obtainable from ignition-lag data for commercial fuels,
that the impression of a sudden ignition can well be gained.
The temperature used as basis for the definition of igni-
tion lag as end state, plays here a lesser part. According
to figure 6a, the temperature rise in the range between
1,300 and 17,000° K. is already so steep for  b = 8,700
that practically the same ignition-lag period would have
to be assumed for both terminal temperatures. The temper-
ature rise based upon the value b = 23,000 (fig. 6b) is
even steeper. This value is in order of magnitude similar
to the exponent involved in methane. The abscissas in
figure 6 are proportional to the time. (See also equa-
tions (5) and (6)).


4. Comparison of Theoretical and Experimental Results

The foregoing ignition-lag formula holds for the
chemical share only. But, if the heating and vaporization
processes play a secondary part compared to the chemical
changes a comparison of the formula with the measured ig-
nition-lag values is appropriate in first approximation.
Should this comparison disclose a good agreement between
test data and formula, it still would afford no proof that
in this case the effect of the thermal processes on the

ignition-lag period is small, but merely show the possi-
bility for it. The basic principles for the determina-
tion of the thermal effects on ignition lag are, however,
so little understood that an inclusion in the interpre-
tation would be premature. For the present, the compari-
son of the test data with a law which, in development of
its formula, corresponds to that for the chemical igni-
tion-lag share is of interest.

The evaluation of ignition-lag tests reveals the test
values to be very closely represented by the chemical-
share formula:

$$z = \frac{e^{b/T} \sqrt{T}}{p^n} a \, \beta \tag{5a}$$

The test data can also be represented in simplified form

$$z = \frac{e^{b'/T} \sqrt{T}}{p^n} a' \tag{9}$$

or

$$z = \frac{e^{b''/T}}{p^n} a'' \tag{10}$$

since the variation of $\beta$ can be equalized by a change
in the value $b$ (then expressed with $b'$ or $b''$); $a'$
and $a''$ are then new constants also, which account for
the omissions in equations (9) and (10) relative to equa-
tion (5a). Figure 7 shows the same ignition-lag test
data by Lindner (reference 13) compared with the three
formulas (5a), (9), and (10). It is apparent that the
effect of the $e$ function is so predominating that the
lesser change of $\sqrt{T}$ and $\beta$ is not important.

The possibility of expressing the ignition-lag test
data by formula similar to the empirical (10) has been
voiced by various research workers on the basis of studies
with methane. The accord of this formula with the test
data is better for gases than for liquid fuels, because
the thermal share of gases is little or not at all appar-
ent. In the high-temperature range particularly the ef-
fect of the thermal share in liquid fuels is pronounced,
because of the marked drop in the chemical share with the
temperature in conformity with the $e$ function. However,
there may be cases where, in the low temperature range, the
time lapse for the thermic processes is considerably

greater. And agreement of test data and formula itself
is no proof of the predominating effect of the chemical
share. Hence, the evaluation of ignition lag test data
of liquid fuels must allow for the thermic share also.

It is not yet clear whether it is permissible to
equate the total ignition lag in first approximation to
the sum of the two shares. The division of the total lag
in chemical and thermal share empirically is extremely
difficult. An approximate division was possible on the
basis of the mathematical determination of the thermal
share and on the basis of comparisons of fuel tests of
widely varying volatility under otherwise identical condi-
tions. The correctness of such a division can be effect-
ed on the basis of comparative tests of fuels with and
without preheating and on the basis of a separate experi-
mental study of the processes during heating of the fuel
droplets. Comparative ignition tests with the gaseous and
liquid phase of the same fuel under way at present are
hoped to provide further information on this subject.

Apart from the experiments illustrated in figure 7,
numerous tests of other research workers (Holfelder reference 2,
fig. 8, and Wolfer*) have equally produced results which
are reproducible by the above formulas. More recent tests
by Professor Nagel with the improved Holfelder equipment
have disclosed a smaller pressure relation for ignition
lag. In most cases value b may be figured constant for
the whole explored range; only in very few cases are ap-
preciable differences noted** in the exponent of
$e^{-b/T}$ at different temperatures. Even bimolecular reac-
tions manifested in isolated cases different activation heat
$Q_a$ in different temperate zones (reference 12), whence it
is very likely that even in complex combinations similar
changes in reaction with temperature are involved.

The fundamental similarity of the experimentally and
theoretically defined laws for ignition lag constitutes a
proof for the assumption that the cause of ignition lag,
apart from the thermal processes, is essentially attrib-
utable to a reaction or combustion combined with heat,

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*Wolfer's tests are described in the present article.

**Thus, for instance, some organic combinations manifest
two different oxidation mechanisms in individual temper-
ature ranges (reference 17 and 18).

which ignites first at the points of most propitious con-
ditions for temperature and mixture ratio. A relation-
ship of the ignition lag in a Diesel engine on excess air
is therefore not involved, because ignition always starts
at the point of most favorable excess air. (For the cool-
ing effect of vaporization, significant with little excess
air, see under sec. 5.)

On the other hand, the shortest ignition lag within
range of the fuel spray occurs at the point where the
necessary mixture ratio and the maximum temperature meet.
In well developed fuel sprays the droplets at the edge are
less dense and the cooling effect of vaporization is less
apparent.


5. Effect of Ignition Lag on the Behavior of the Engine

Especially at Altitude

The ignition-lag periods measured in engine tests
usually made at the same pressure and temperature are in
general smaller than in calorimetric bombs. The reason
for this was commonly ascribed to the varying degrees of
turbulence. But there can be no substantial turbulence
effect unless the air motion procuces more favorable heat-
ing conditions for the ignitable fuel particles. Small,
(reference 3) in his bomb tests with and without turbulence
could detect no measurable difference in ignition lag.
Hence it is to be assumed that the turbulence has in gen-
eral no essential effect on the ignition lag, even though
the conclusion suggests itself on the basis of various
other investigations that recorded differences might be
traceable to turbulence. Greater ignition lags have been
recorded on numerous occasions with low-speed engines re-
ferred to equal pressure and temperature, but these are
caused partly by lower compression. Any decision of the
extent of this phenomenon attributable to turbulence is
difficult in engine tests. There is a possibility that
hot spots in the engine cylinder might affect the ignition
lag considerably.

The engine operating cycle has very little effect on
ignition lag (fig. 9). Engines operating on different
principles have disclosed little difference in absolute
values and little difference in temperature effects. Sim-
ilar agreement prevails for the relation of ignition lag
to specific weight (fig. 9) and temperature (fig. 10).

The curves refer to identical fuels and optimum engine adjustment (appropriate nozzles). The temperature effect becomes so much less as the temperature is higher and becomes practically insignificant at around 700° C. The pressure effect is more noticeable for low than for high specific weight.

In the presentation of the ignition lag values recorded in the engine, it is to be noted that different lag periods can occur at the same compression if the spray period is changed. The magnitude of the ignition lag depends upon the amount of heating by the temperature of the air, which in an engine varies during the compression cycle approximately according to a sinusoidal function with the time. Hence, the more the ignition-lag periods approach the apex of this sinusoidal line the shorter the recorded-lag period will be. The differences due to change in spray periods are shown in two curves in figure 10.

The recorded pressure relation is, in order of magnitude, in close agreement with the theoretical. It should be borne in mind that the rate of vaporization rises only with one power of the pressure whose exponent is less than one.

With the ignition lag, the engine performance itself is dependent on altitude. Therefore, engines with high compression and consequently small ignition lag have a smaller power drop with altitude than those with low compression (fig. 11).

The experiences with pressure and temperature in their relation to ignition lag are of particular importance for the control of the operating cycle and for the power computations of Diesel engines at altitude.

The power drop of the Diesel engine in relation to altitude is, according to past test data, unlike that of the Otto engine (fig. 11). At low heights - up to around 2 kilometers (6,500 feet) - a smaller power reduction is obtainable with a Diesel engine, because the excess air permissible at sea level for cruising load can be lowered with the usual control for increasing height without increasing the thermal stresses of the engine over those at sea level. At greater heights, of course, the output of a Diesel engine drops in general more than in an Otto engine and principally because of the rise in ignition lag as a

result of lower pressure and low temperature at terminal compression.

According to the pressure-time card (fig. 12), the ignition starts later with increasing height, thus vitiating the performance and raising the fuel consumption. This phenomenon is particularly vitiating in engines with divided combustion chamber, where, as a result of the lowered air density, the ignition in the chamber occurs so late that conditions in the main chamber are as a result of the already lowered pressure unfavorable for the subsequent combustion. In air-cell engines only a relatively small quantity of air (excess air factor very small) is available in the cell. Because at low air density and low air temperature (at altitude) the ignition-lag periods are long, more fuel can vaporize during this lag period. Owing to the small amount of air available, a marked cooling takes place through which in certain circumstances the ignition may stop altogether.

But with smaller ignition lag under normal operating conditions, the ignition already starts at the spray edge while fluid fuel is still present in the spray core, so that the cooling at the points of ignition as well as on the whole becomes less. In altitude tests with a Lanova engine (its principle is described in reference 19) the ignition stopped quite abruptly at lowered excess air, as became manifest for instance at an induction pressure equivalent to an altitude of about 13,125 feet and without changed spray timing ($\epsilon = 12.5$) with an excess of air of $\lambda < 1.2$; at higher compression ($\epsilon = 15$) the ignition missed only after reaching an induction pressure equivalent to 19,685 feet and $\lambda < 0.85$. A check of a vaporization test carried out on the basis of Wentzel's calculation (reference 14) disclosed that at 80 percent vaporization of fuel the air temperature in the cell would have to drop to $270^\circ$ C. As at this low temperature ignition can no longer take place within the time interval required at 1,500 r.p.m., it follows that a large portion of the fuel is expelled in nonvaporized state from the cell.

The behavior at altitude of a Diesel engine can generally be improved by raising the compression, which affords a higher temperature of compression and a high pressure of compression and consequently a smaller ignition lag, or by adaptation of the penetration of the fuel spray to the low density of the charging air and by earlier ignition at increasing height. Figure 13 illustrates pressure-time rec-

ords with higher compression ($\epsilon = 15$) for different heights
than shown in figure 12.

But along with the undesirable effect of the too-long
ignition lag, the extremely short lag is equally as unde-
sirable in most cases. Only limited air velocities are
available for carburetion, hence a minimum time interval
is necessary prior to start of ignition and during incip-
ient combustion in order to assure the distribution of the
fuel in the cylinder. If the ignition starts too soon
this process of carburetion is often considerably disturbed.

## III. DETONATION

### 1. Physical and Chemical Phenomena

### Accompanying Engine Knock

Investigations into the detonation characteristics of
engines, especially into the knock limitations under varied
operating conditions have led to the conclusion that the
detonation process can be definitely influenced by the
pressure and temperature of the inducted air (reference 33).
The observations point to a reaction in the unburnt portion
of the gas mixture compressed by the advance of the flame
front as the principal cause of the detonation rather than
vibration phenomena. According to the findings of the ex-
periments related hereinafter, the process of combustion
and the creation of detonation is - with due regard to the
previously held views, especially by Ricardo (reference 20)
wherein detonation is attributable to a sudden combustion
of the unburnt portion of the mixture - approximately as
follows:

While the combustion front, starting at the spark
plug, advances at a speed dependent on the turbulence, ex-
cess of air, pressure and temperature of the mixture,
there is a slow reaction or burning in the unburnt portion
at about the same rate as applies to the chemical propor-
tion of the ignition lag in Diesel engines. The rate of
this reaction is governed by the pressure and temperature
of the unburnt portion. This temperature increases as a
result of the displacement effect of the burning part even
after dead center. With high compression (for instance,
$\epsilon = 8$) and at $80°$ charging air temperature the temperatures
of the unburnt part rise in the range between $20°$ crank

angle B.T.C. and 10° A.T.C. from around around 450° to 650° C. The slow combustion process is followed by a continuous temperature rise in the unburnt part, which in turn speeds up the rate of combustion so that, according to equation (8) and the measured values spontaneous ignition is to be expected in the unburnt mixture soon after T.C.

A rough check of the experimental data itself indi- cates that the terminal temperature of the unburnt part due to compression at the instant of incipient knock can- not be considered as the sole cause of detonation, but that the concept of a supplementary slow reaction is in better agreement with the experimental data. (This is also in accord with the measurements by Withrow and Boyd (reference 29), who observed the slowing up of the flame front prior to detonation, in contrast to Rothrock and Spencer (reference 30), who observed this slowing up of the flame front only in several cases). As to the course of this reaction, it was definitely established that the tem- perature and furthermore the pressure of the unburnt part are of primary significance.

2. Experimental Results and Theoretical Interpretation

of Detonation Tests

The available methods of objective measurement of the detonation are as yet quite inaccurate. The measurements are chiefly based upon measuring the rate of pressure rise or on optical observation of the flame front during com- bustion. A much simpler, but more unreliable method, is afforded by the observation of the detonation noise.

For the exploration of the detonation process either the individual process in the cylinder - especially through measurement of the processes in the flame front and in the unburnt mixture portion - is studied or else the knock lim- itations under varying test conditions are chosen as a basis. Both methods are of equal promise.

In the following, it is attempted to trace the deto- nation by the method of changing knock limitations.

Figure 14 illustrates the knock limitations with changing the spark advance. In order not to exceed these limitations, the pressure in the inlet pipe was lowered at

greater spark advance.  The changed limit and the compres-
sion ratio  $\epsilon$  along with the correlated mean pressures
$p_e$  are shown in figure 15.  The accuracy of the obtained
limitation through audition is seen from the scattering of
the test points.

    The test results permit the conclusion that the re-
action processes in the unburnt mixture are the primary
cause of detonation, and the pressure waves secondary.
Pressure waves accelerate the internal reaction up to ig-
nition in the mixture already close to the ignition bound-
ary.  If the temperature and pressure rise, due to an ex-
isting pressure wave, suffices during the interval of pas-
sage of the wave to heat the mixture, already close to
spontaneous ignition as a result of the pre-reaction, to
visible ignition, the flame front can pass through the
space still replete with unburnt mixture at sonic veloc-
ity.

    In order to check these concepts and assumptions, the
detonation experiments were evaluated on the assumption
that the reaction presumed to be the chief cause of deto-
nation follows the same laws as the reactions causing the
spontaneous ignition in ignition lag.  Hence the equation,

$$\frac{d\,[B]}{dz} = \frac{p^n\,d}{e^{b/T}\,\sqrt{T}} \tag{8}$$

which, at constant excess of air, gives the correct presen-
tation of the relation between the ignition lag of gases
on pressure and temperature with the constants to be de-
fined from the measurement, as derived from the results
concerning the dependence of the chemical proportion of
the ignition lag on pressure and temperature.  In this
attempted evaluation of the detonation tests the reaction
in the unburnt part which leads to detonation is assumed
to be constant.  But various investigations have shown the
reaction in such gasoline mixtures to be extremely varying
at different temperature ranges.  It is perfectly possible
that similar phenomena take place in detonation.  When, in
spite of it, it was possible on the basis of such an eval-
uation to reach the conclusion that a uniform reaction is
feasible, it still does not prove it, because such agree-
ment can also be obtained if in one certain range a pre-
dominating reaction takes place with such laws.

In the evaluation, the pressure and temperature of the unburnt mixture at adiabatic compression were determined from the indicator cards in relation to crank angle. With the aid of the thus obtained temperature curve, a new temperature curve for the unburnt portion was established by progressive integration on the basis of the above formula. In this new curve, the temperature rise due to advancing flame front and to the internal combustion was allowed for.

If the detonation is to be explained by a reaction in the present form, a portion of the mixture must still be unburnt (reference 21) at the moment when the reaction velocity and the temperature rise become very rapid. In experiments based upon knock limitations, the flame front must at this instant have advanced far enough so that a small portion of the mixture in the cylinder still remains unburnt. Since unburnt parts are equally existent behind the illuminating flame front, it is possible under certain circumstances that detonation occurs even in cases where the flame front has almost traversed the combustion chamber (reference 30). For that reason, an exact evaluation of the experiments by this method necessitates an exact record of the time interval and crank angle, respectively, at which detonation starts, and the movement of the flame front itself must be known.

The time interval of incipient detonation was checked by quartz indicator and the evaluation of the combustion process was accomplished by stroboscopic record of the indicator card and glow lamp indicator. The combustion process was determined from the energy balance for the combustion and expansion cycle (reference 22). (See also combustion studies by Drinkwater and Egerton (reference 23). The result is illustrated in figure 16. Here the flame front has reached the end of the cylinder at about 20° A.T.C., i.e., the combustion for this time interval has ended.*

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*This method of determining the combustion process is in close accord with direct measurements of flame fronts in the cylinder. The paths of the flame fronts as measured by Bouchard, C. Fayette Taylor, and E. S. Taylor, correspond to a similar transformation of the fuel quantities, as established in the present experiments. Rassweiler and Withrow (reference 26) measurements also agree with the present evolutions. The direct measurements of the path of the flame front merit preference over the theoretical determination carried out here. (For flame-front measurements, see also F. Kneule (reference 27).

Measurable or auditive detonation could occur only
if the detonation in the unburnt part occurs at the lat-
est in the range between 5° and 15° crank angle. The
combustion process shown varies considerably, however,
with the operating condition. When evaluating a large
number of indicator cards, it was found that the crank
angle, at which combustion is terminated, and the entire
combustion process is first of all dependent upon the ig-
nition period and shifts almost like the ignition, that
is, retarding the ignition 10° is followed by a delay of
about 10° in combustion. In several cases it was also
observed that the difference of the crank angles in the
combustion process was a little less than the spacing of
the spark timing. The r.p.m. is of little influence.
This result agrees with the fact that the increase in ig-
nition speed is almost proportional to the r.p.m. and
approximately proportional to the speed of turbulence.
The combustion process in relation to crank angle is lit-
tle influenced by changing compression, air temperature,
or charge pressure, while a change in excess of air works
profound changes in combustion (reference 30, also 31).
In other words, all influences affecting the rate of ig-
nition, influence the combustion process. Hence the
marked difference in time interval or crank angle involv-
ing the detonation with changed excess of air and spark
advance (reference 30) and the minor difference in changes
in initial temperature and pressure.

In consideration of these viewpoints the above evalu-
ation made it possible to express in one equation of the
form of equation (8) the explored relationships - mutual
change of pressure and temperature of the aspirated air
(throttling and overcharging) and the change of the spon-
taneous ignition and the compression. In other words, the
mean temperature variation could be so expressed in a re-
lation that a rapid temperature rise was computed at the
point where the indicator card predicted the incipient
detonation. Ignition-lag studies of fuels for Otto en-
gines are available only in parts. Lindner has made some
ignition-lag measurements on gasoline sprays, but his
findings are inapplicable to the evaluations because in
the Otto engine the fuel is practically completely vapor-
ized at the end of compression, so that the heating proc-
esses of the fuel and the vaporization at ignition by in-
cipient detonation are no longer apparent. The decision
concerning the applicability of constants obtained from
the ignition-lag measurements for detonation tests must be
held in abeyance pending further experimentation with vap-
orized fuels. These measurements are being made once with

adiabatic compression as applied by H. T. Tizard and D. R. Pye (reference 28) and once by blowing fuel vapor into hot air.

Figures 17 and 18 show temperature curves obtained with changes in compression and initial temperature from tests at knock limitations. The application of the same formula to test series beginning in the detonation-free zone and terminating in the severe detonation zone gives the temperature curves illustrated in figure 19. (The test series of figure 19 refers to a different fuel from that of figures 17 and 18.) The temperature rise for detonating operation occurs at a crank setting where much fuel is still unburnt, for detonation-free operation the temperature rise is small shortly before terminated combustion in the unburnt part. This would turn into a rapid burning only at a later interval. The evaluation is not to be interpreted that the temperature variation in the unburnt part actually corresponds to the curves shown in the plots. They are merely intended to show that the detonation process can be explained with a reaction, the speed of which can be represented by the reciprocal value of a pressure power and an e function of the reciprocal value of the temperature without making any predictions as to the time rate of change.

On the basis of the above reasoning, it is to be expected in agreement with the customary explanation of the effect of antiknocks (references 24 and 25), that the interaction of lead will result in a check of the reaction (for instance, chain interrupting). The effect of tetra ethyl lead will probably not show as a change in the value b of the reaction formula which characterizes essentially the molecular properties, but in a changed d in a constant factor in the reaction formula. If the enhanced detonation tendency is equalized only by a change in pressure, the reaction formula undergoes a change insofar as at knock limitation the value $p^n$ and hence p must be changed for a constant factor in correspondence with the change in d.

The evaluation included the experiments of P. Giertz with supercharge and increased air temperature at different spark advances and excess of air. This was supplemented by investigations of the knock limitations under changed pressure and temperature before the engine, as well as for changed spark advance and compression.

The test results for the detonation limit of gasoline with and without leaded fuel are given in figure 20. The detonation reducing effect was mathematically allowed for with a change in  d  with a constant factor, which corresponds to a proportional change of the admissible value for p. The experimental determination was in good accord with this reasoning. The solid curves represent the experimental data, the dashed curves the experimental values with leaded fuel reduced by a constant factor. The agreement is satisfactory.

The above method of evaluation produced satisfactory results in several test series on two engines. To what extent and with what limitations the investigating methods are practical remains to be proved in further engine tests.


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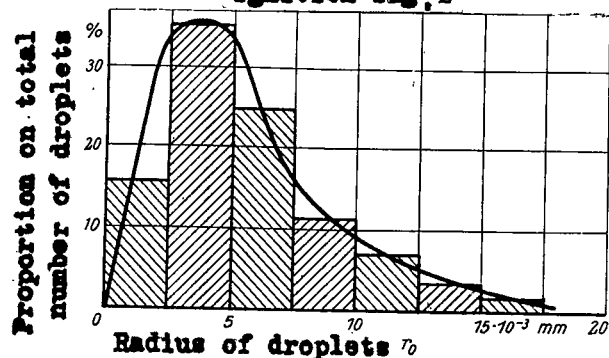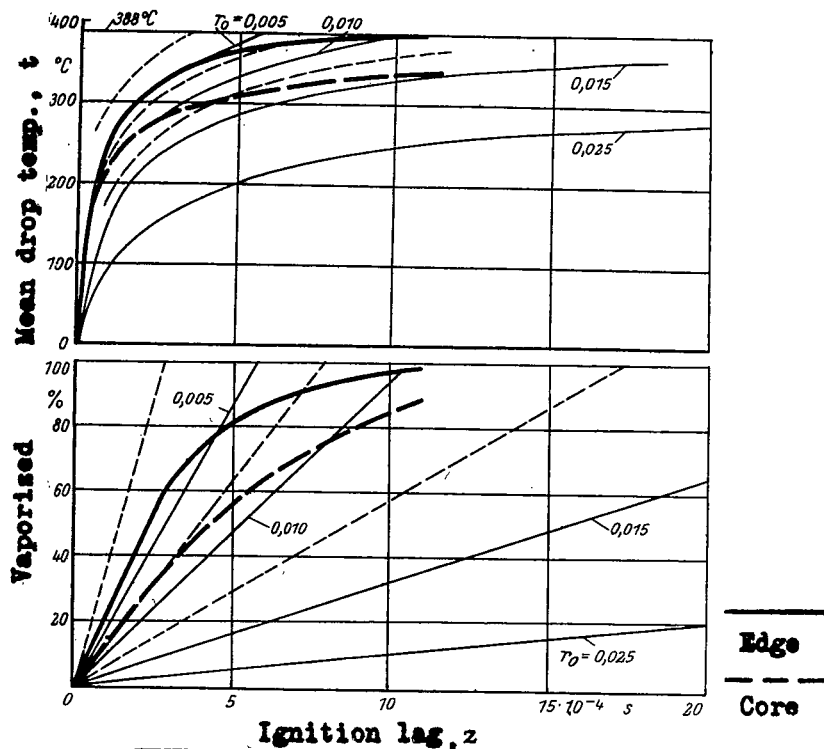
Figure 1.- Vaporization in fuel spray and at spray boundary.
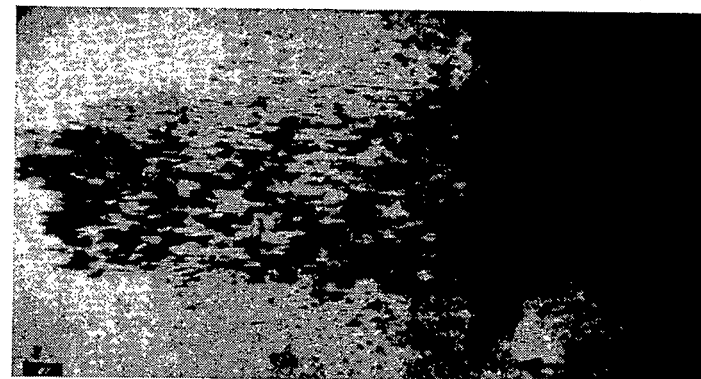


Figure 2.- View of forward portion of spray(in transmitting light 5X.)
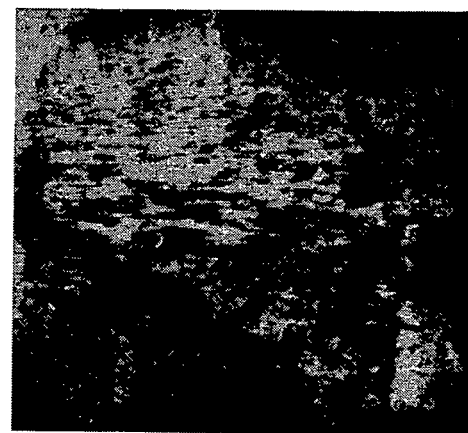


Figure 3.- View of central portion of spray (transmitting light; 5X)

$$\int \frac{e^{8700/T}}{\sqrt{T}} \, dT \text{(proportional to time)}$$
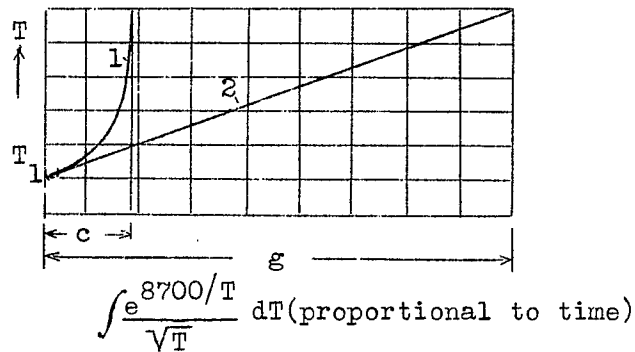
Figure 4.- Temperature rise during reaction with allowance for re-
action velocity:(1) at reaction velocity equivalent to
initial temperature:(2) in relation to temperature T.

$T_1$ = Initial temperature

$\beta = c/g$
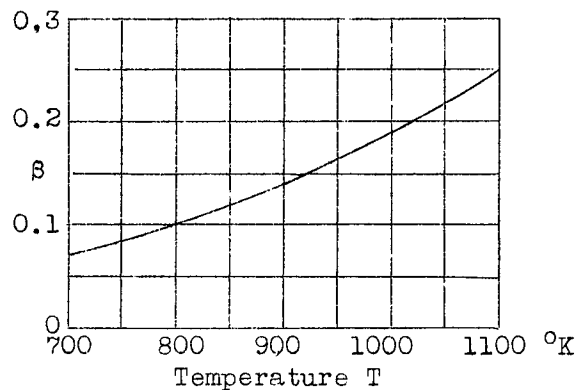
Figure 5.- Change of value $\beta$ with temperature T
$Qa/R = 8700$.
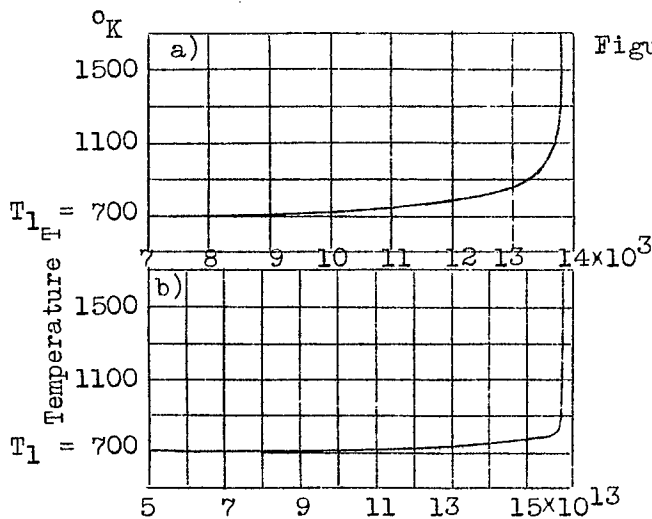
Figure 6.- Presentation of integral

$$\int_{T_1}^{T} \frac{e^{b/T}}{\sqrt{T}} \, dT \text{ between}$$

$T_1 = 700$ °K and any
other temperature T(made
up to 1700°K) for b = 8700
(top) and b = 23,000(bottom).

$$\text{a) } z = \frac{e^{b/T} \sqrt{T}}{p_n} \, a\,\beta, \text{ where} \begin{cases} b = 8740 \\ n = 1,10 \\ a = 1,20 \cdot 10^{-6} \end{cases}$$

$$\text{b) } z = \frac{e^{b'/T} \sqrt{T}}{p_n} \, a', \text{ where} \begin{cases} b' = 6850 \\ n = 1,07 \\ a' = 1,145 \cdot 10^{-6} \end{cases}$$

$$\text{c) } z = \frac{e^{b''/T}}{p_n} \, a'', \text{ where} \begin{cases} b'' = 6330 \\ n = 1,08 \\ a'' = 6,6 \cdot 10^{-5} \end{cases}$$
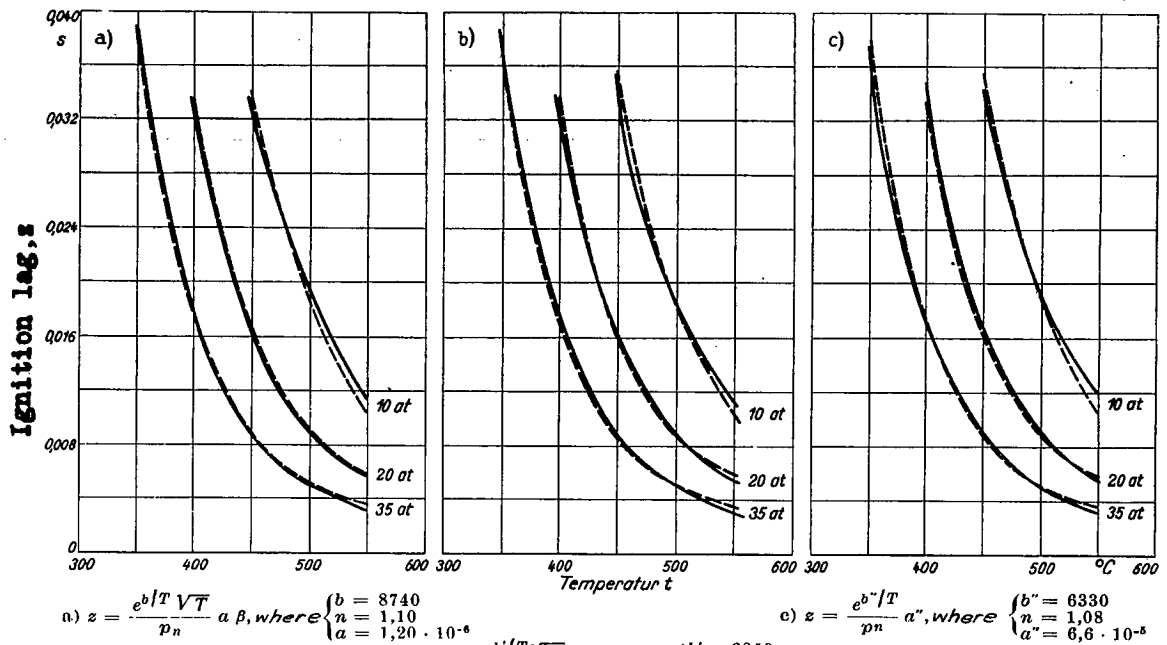
**Figure 7.– Ignition lag plotted against pressure and temperature.** (The dotted curves are obtained from experiments).
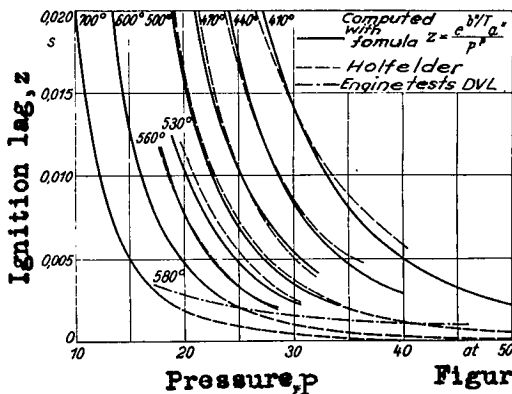


**Figure 8.– Ignition lag plotted against pressure and temperature.**



1– Prechamber engine $\epsilon = 14$ ; 1500 r.p.m.
2– Lanova    "    $\epsilon = 12.5$; 1490 r.p.m.
3–   "    "    $\epsilon = 15$ ; 1490 r.p.m.
4– Direct injection $\epsilon = 12.2$
5– Otto cycle engine; $N = N_0 \dfrac{p}{p_0} \sqrt{\dfrac{T_0}{T}}$

**Figure 11.– Diesel engine performance against altitude.**



**Figure 20.– Pressure in intake pipes corresponding to knock limitations at different temperatures of inducted air for plain and leaded gasoline.**
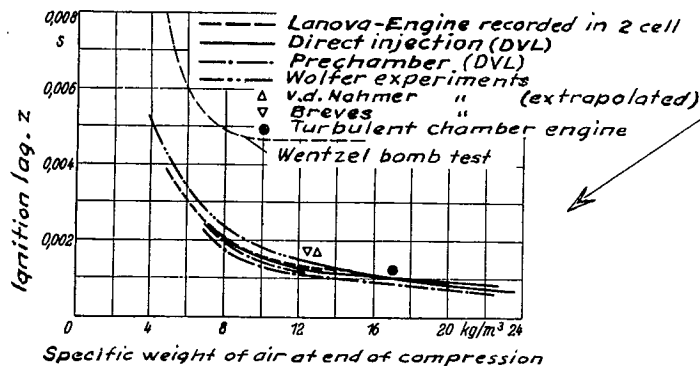
Figure 9.- Ignition lag against specific weight of air at end of compression for different Diesel cycles and bomb tests.
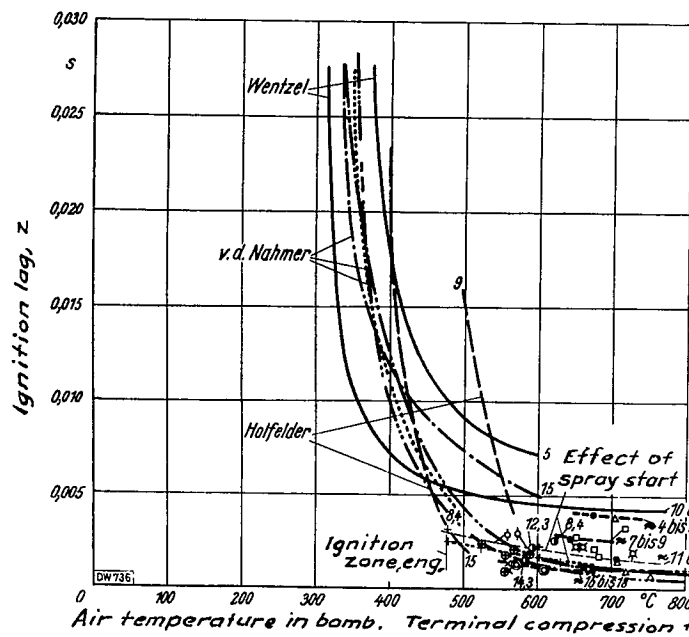


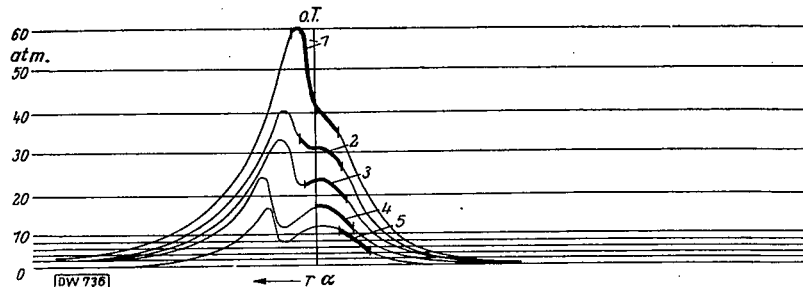Figure 10.- Recorded relationship between ignition lag and temperature, engine and bomb tests.

Figure 12.— Indicator cards at different induction pressures p Lanova
cycle $\epsilon = 12.5$; n = 1490 r.p.m.

1,p=1.03 at abs. equiv. to 0    m alt. $p_e$=6.04 at.; start of spray 13° B.T.C.
2,p=0.80 "   "      "     " 2080m "  . $p_e$=5.25 at.;   "    "    "   14° B.T.C.
3,p=0.62 "   "      "     " 4160m "  . $p_e$=3.14  "  ;   "    "    "   18° B.T.C.
4,p=0.54 "   "      "     " 5200m "  . $p_e$=2.20  "  ;   "    "    "   21° B.T.C.
5,p=0.48 "   "      "     " 6000m "  . $p_e$=1.40  "  ;   "    "    "   23° B.T.C.

The solid portion indicates the spray period. The height data refer to alt-
itude of equal pressure.
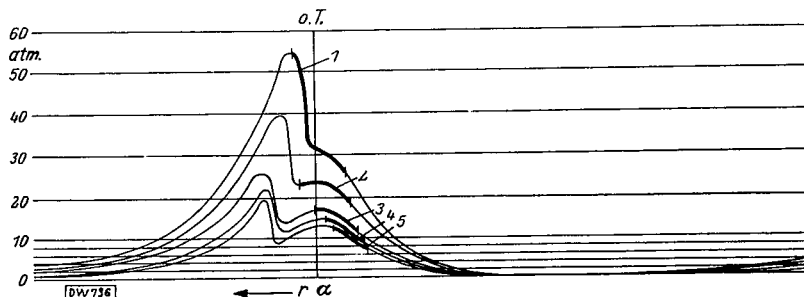


Figure 13.— Indicator cards of cylinder main chamber at
different p and $\epsilon$ =15.

1,p=1.03 at abs. equiv. to 0    m alt. $p_e$=5.96 at.; start of spray   9° B.T.C.
2,p=0.81 "   "      "     " 2050m "   $p_e$=4.40  "  ;   "    "    "    10° B.T.C.
3,p=0.62 "   "      "     " 4070m "   $p_e$=3.65  "  ;   "    "    " 12.5° B.T.C.
4,p=0.47 "   "      "     " 6220m "   $p_e$=2.35  "  ;   "    "    "    16° B.T.C.
5,p=0.345 "  "      "     " 8380m "   $p_e$=0.85  "  ;   "    "    "    23° B.T.C.

The solid portion corresponds to spray period.
Height data refer to equal pressure height.
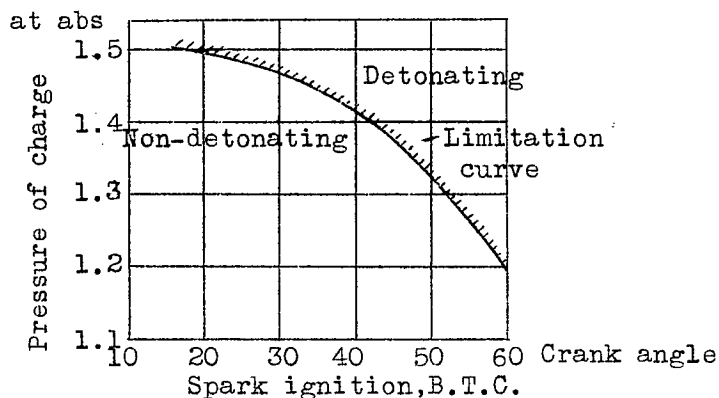
Figure 14.- Knock limitations plotted against spark
ignition.

a.    $p_e$(OZ 87) 100°C
b.    $p_1$(OZ 87) 100°C
c.    $p_e$(OZ 73) 20 °C
d.    $p_e$(OZ 73) 100°C
e.    $p_1$(OZ 73) 20 °C
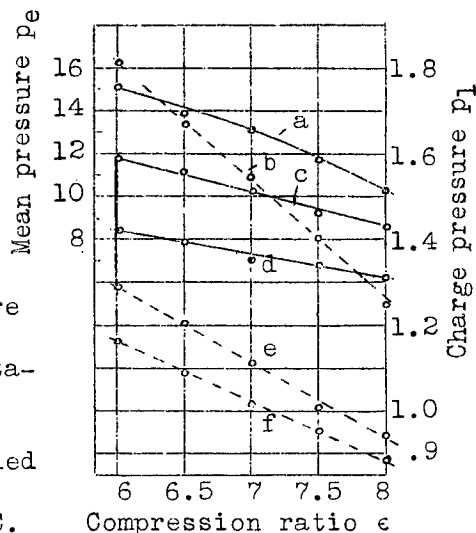f.    $p_1$(OZ 73) 100°C

Figure 15.- Charge pressure
            $p_1$ and mean
pressure $p_e$ at knock limita-
tions against compression
ratio $\epsilon$ .
OZ 73 Gasoline BO not leaded
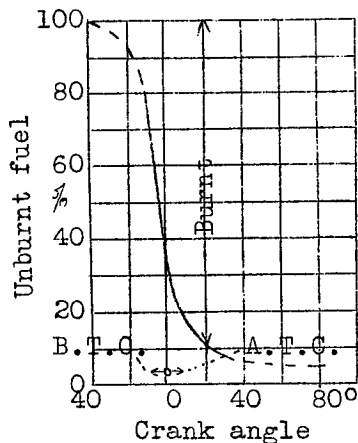OZ 87     "        "   leaded
$\lambda$ = 0.9; Spark ignition 38° B.T.C.



Figure 16.- Combustion versus crank
            setting.

Spark ignition 38° B.T.C.

n = 2600 r.p.m.

Figure 19.- Temperature distribution for unburned fuel quota in cylinder under conditions of Figs. 17 and 18 best for a test series starting in the detonating and terminating in the knock-free zone air temperature: 80°C ,spark ignition: 38° B.T.C.
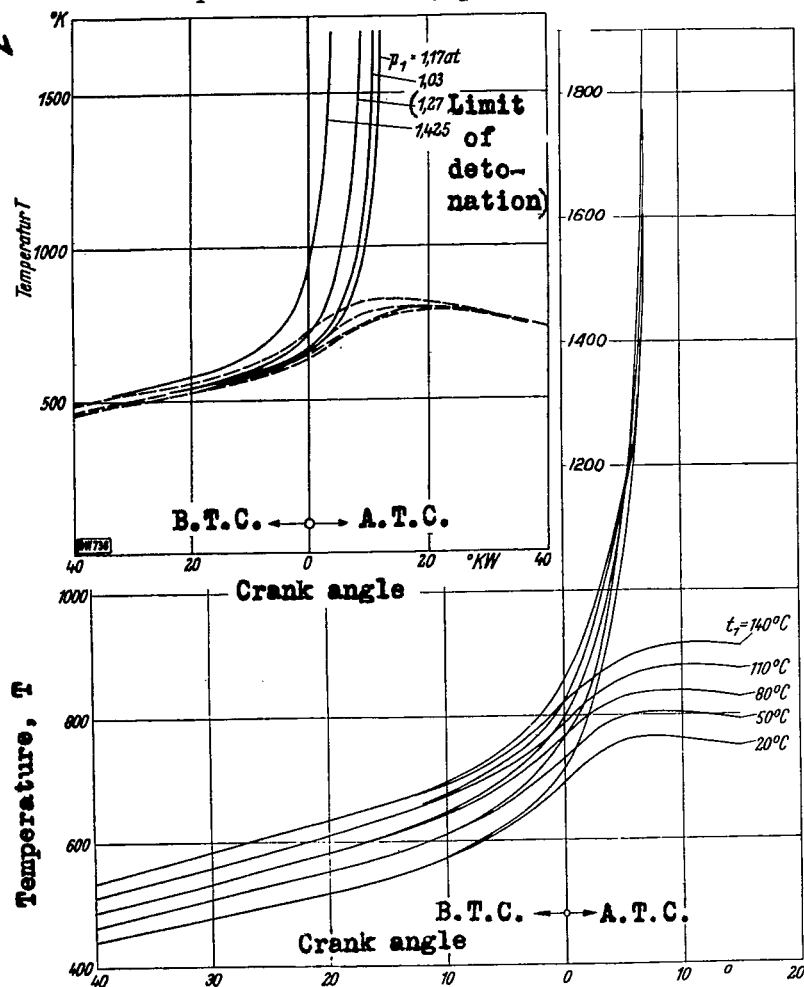


Figure 17.-Mixture temperature T versus start of ignition and initial temperature T ,at constant compression ratio ε=6.

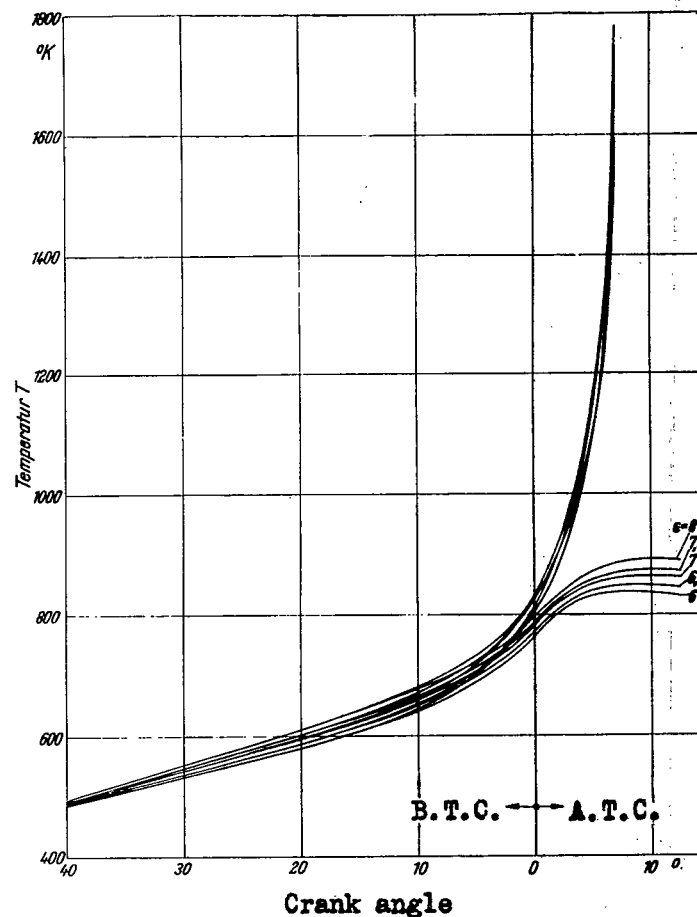Figure 18.- Mixture temperature T versus start of ignition and compression ratio ε at constant initial temperature t₁ = 80°C